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An assessment of threats to the American power grid

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Abstract

Concern has been raised that the electrical grid of this nation is vulnerable to prolonged collapse. The postulated mechanisms are geomagnetic storms, electromagnetic pulse attacks (EMP) via a high altitude nuclear detonation, cyberattacks, and kinetic attacks. The likelihood of such events and the consequences to the American public of a protracted electric power failure are reviewed.

Background

The potential vulnerabilities of the American power grid for a prolonged collapse have been the focus of several Congressional hearings and commissions. There has, however, been no formal analysis of this issue in the academic peer reviewed literature. To prepare this manuscript, Congressional testimony, Congressional Commission reports, Federal reports, and all published scientific papers dealing with electrical power grid vulnerability, grid collapse, geomagnetic storms, electromagnetic pulse, cybersecurity, and cyberattacks as regards power plants (searched through google) were reviewed.

The intent of this report is to provide an objective summary of the current science and controversies on this issue for policy makers and the interested public.

Introduction

In testimony before a Congressional Committee, it has been asserted that a prolonged collapse of this nation's electrical grid—through starvation, disease, and societal collapse—could result in the death of up to 90% of the American population [1].

There is no published model disclosing how these numbers were arrived at, nor are we able to validate a primary source for this claim. Testimony given by the Chairman of the Congressional EMP Commission, while expressing similar concerns, gave no estimate of the deaths that would accrue from a prolonged nationwide grid collapse [2].

The power grid is posited to be vulnerable to geomagnetic storms generated by solar activity, electromagnetic pulses (EMP, also referred to as HEMP) produced by high altitude nuclear detonations, cyberattack, and kinetic (physical) attack. Evidence for and against the validity of each of these threats follows below. Much of the knowledge on these matters is classified. The studies for and against EMP, other than for limited testing of a few components of the infrastructure by the EMP commission, are based not on physical demonstrations but mathematical models and simulations. Moreover, the underlying physics and technology involved—the electrical engineering and materials science—is likely beyond the understanding of the reader, and certainly beyond that of these writers. With these limitations in mind, we proceed.

The electrical grid

HV (high voltage) transformers—transmitting voltages of greater than 100 kV—are what make it possible to send electricity over great distances to thousands of substations, where smaller transformers reduce the voltage.

HV transformers are the weak link in the system, and the Federal Energy Regulatory Commission (FERC) has identified 30 of these as being critical. The simultaneous loss of just 9, in various combinations, could cripple the network and lead to a cascading failure, resulting in a "coast-to coast blackout" [3].

If the HV transformers are irreparably damaged it is problematic whether they can be replaced. The great majority of these units are custom built. The lead time between order and delivery for a domestically manufactured HV transformer is between 12 and 24 months [4], and this is under benign, low demand conditions.

The first practical application of the transformer was invented in the USA by William Stanley, but largely as a consequence of American trade policy ("It doesn't make any difference whether a country makes potato chips or computer chips"- attributed to Michael Boskin, Chairman of President George H W Bush's Council of Economic Advisors) [5] there is little manufacturing capability remaining in the USA. Worldwide production is less than 100 per year and serves the rapidly growing markets of China and India. Only Germany and South Korea produce for export.

Ordered today, delivery of a unit from overseas (responsible for 85% of current American purchasing) would take nearly 3 years [6]. The factory price for an HV transformer can be in excess of $10 million—too expensive to maintain an inventory solely as spares for emergency replacement.

Potential mechanisms of collapse

Geomagnetic storms

Geomagnetic storms are due to coronal mass ejections (CMEs)—massive eruptions of plasma expelled from the sun's corona. Plasma is the fourth fundamental state of matter, consisting of free electrons and positively charged ions. The sun, like all stars, is plasma.

Coronal mass ejections often occur with solar flares, but each can take place in the absence of the other. The latter emits radiation in all bands of the electromagnetic spectrum (e.g., white light, ultraviolet light, X-rays, and gamma rays) and unlike CMEs, affect little more than radio communications.

CME's take several days to reach the Earth. The radiation generated by solar flares on the other hand arrives in 8 min.

Coronal mass ejections carry an intense magnetic field. If a storm enters the earth's magnetosphere, it causes rapid changes in the configuration of the earth's magnetic field. Electric current is generated in the magnetosphere and ionosphere, generating electromagnetic fields at ground level. The movement of magnetic fields around a conductor, i.e., a wire or pipe, induces an electric current. The longer the wire, the greater the amplification. The current induced is akin to DC (direct current), which the electrical system poorly tolerates. Our grid is based on AC. The excess current can cause voltage collapse, or worse, cause permanent damage to large transformers.

The current flowing through HV transformers during a geomagnetic disturbance can be estimated using storm simulation and transmission grid data [7]. From these results, transformer vulnerability to internal heating can be assessed.

The largest recorded geomagnetic storm occurred Sept 1–2, 1859—the Carrington event, named after the English amateur astronomer, Richard Carrington. Auroras were seen as far south as the Caribbean. Campers in the Rocky Mountains were awakened shortly after midnight by "an auroral light so bright that one could easily read common print. Some of the party insisted it was daylight and began preparation for breakfast" [8]. Telegraph wires transmitted electric shocks to operators and ignited fires.

In May 1921, there was another great geomagnetic disturbance (GMD), the railroad storm. The National Academy of Sciences estimates that if that storm occurred today, it could cause 1–2 trillion dollars damage and full recovery could take 4–10 years [9].

The basis for this assertion is a presentation made by J Kappenman of Metatech, the Goleta California engineering consulting firm, given as part of the NAS Space weather workshop titled "Future Solutions, Vulnerabilities and Risks", on May 23, 2008. The simulation asserts that a 1921 intensity storm could damage or destroy over 300 transformers in the US, and leave 130 million people without power [10]. Elsewhere, Kappenman states that in a worst case situation, geomagnetic disturbances could instantly create loss of over 70% of the nation's electrical service [11].

In March 1989, a geomagnetic storm caused collapse of the power grid in Quebec, leaving 6 million without power for 9 h. NERC (the North American Electric Reliability Council), a self-regulated trade organization formed by the electric utility industry, asserts that the blackout was not due to overheating of transformers from geomagnetically induced current, but to the near-simultaneous tripping of seven relays, and this is correct [12]. The rapid voltage collapse (within 93 s) likely prevented transformer thermal damage. The same storm, however, destroyed a major transformer at the Salem nuclear plant in New Jersey [13]. The 1989 Hydro-Quebec storm was 1/10th the intensity of the 1921 Railroad Storm [14].

A report for Lloyd's in 2013 states a Carrington-level extreme geomagnetic storm is almost inevitable in the future. Using its own models and simulations, it puts the US population at risk at between 20 and 40 million, with the outages lasting up to 1–2 years [15].

Because of geography and ground conductivity, the risk of a transformer sustaining damage is 1000 times greater in some US counties than in others. The highest risk is to the counties along the corridor between Washington DC and New York [16].

The first written account of a solar storm is possibly in the book of Joshua. Written reports of aural sightings by Greeks and Romans begin in 371 BC.

A Carrington-level storm narrowly missed the earth in 2012 [17]. NASA has produced a video on the CME [18]. Formerly considered a 1 in 100-year event, the likelihood of a Carrington intensity storm striking the earth has most recently been placed at 12% per decade [19].

Mitigation

The EMP Commission, in its 2008 report, found that it is not practical to try to protect the entire electrical power system or even all high-value components. It called however for a plan designed to reduce recovery and restoration times and minimize the net impact of an event [20]. This would be accomplished by "hardening" the grid, i.e., actions to protect the nation's electrical system from disruption and collapse, either natural or man-made [21]. The shielding is accomplished through surge arrestors and similar devices [22]. The cost to harden the grid, from our tabulation of Congressional EMP figures, is $3.8 billion.

There has been no hardening of the grid

The commission and organization that are responsible for public policy on grid protection are FERC and NERC. FERC (The Federal Energy Regulatory Commission) is an independent agency within the Department of Energy. NERC, the self-regulatory agency formed by the electric utility industry, was renamed the North American Electric Reliability Corporation in 2006.

In June of 2007, FERC granted NERC the legal authority to enforce reliability standards for the bulk power system in the USA. FERC cannot mandate any standards. FERC only has the authority to ask NERC to propose standards for protecting the grid.

NERC's position on GMD is that the threat is exaggerated.

A report by NERC in 2012 asserts that geomagnetic storms will not cause widespread destruction of transformers, but only a short-term (temporary) grid instability [23]. The NERC report did not use a model that was validated against past storms, and their work was not peer-reviewed.

The NERC report has been criticized by members of the Congressional EMP commission. Dr. Peter Pry asserts that the final draft was "written in secret by a small group of NERC employees and electric utility insiders…. The report relied on meetings of industry employees in lieu of data collection or event investigation" [22].

NERC, in turn, criticizes Kappenman's work. NERC states that the Metatech work cannot be independently confirmed [24]. NERC reliability manager Mark Lauby criticized the report for being based on proprietary code [24]. Kappenman's report, however, received no negative comments in peer review [24].

The NERC standards

The reliability standards and operational procedures established by NERC, and approved by FERC, are disputed [25]. Among the points are these:

1. The standards against GMD do not include Carrington storm class levels. The NERC standards were arrived at studying only the storms of the immediate prior 30 years, the largest of which was the Quebec storm. The GMD "benchmark event", i.e., the strongest storm which the system is expected to withstand, is set by NERC as 8 V/km [26]. NERC asserts this figure defines the upper limit intensity of a 1 in 100-year storm [26]. The Los Alamos National Laboratory, however, puts the intensity of a Carrington-type event at a median of 13.6 V/km, ranging up to 16.6 V/km [27]. Another analysis finds the intensity of a 100-year storm could be higher than 21 V/km [28].

2. The 15–45 min warning time of a geomagnetic storm provided by space satellites (ACE and DSCOVR) will be insufficient for operators to confer, coordinate, and execute actions to prevent grid damage and collapse.

Testimony of Edison Electric Institute official Scott Aaronson under questioning by Senator Ron Johnson in a hearing before the Senate Homeland Security and Governmental Affairs Committee in 2016 encapsulates some of these issues. Video of the exchange is available on the web [29]. The Edison Electric Institute (EEI) is the trade association that represents all US investor-owned electric companies.

Johnson: Mr. Aaronson, I just have to ask you – the protocol of warning 15–30 min – who is going to make that call? I mean, who is going to make that call for a massive geomagnetic disturbance, that nobody knows how many of these transformers are going to be affected. Who is going to make that call to shut them off line – to take them off line – so those effects do not go through those wires and destroy those large transformers that cannot be replaced?

Aaronson: So, the grid operators are tightly aligned. We talked about the fact that there are 1900 entities that make up the bulk electric system. There are transmission operators and so on…

Johnson (interrupting): Who makes the call? Who makes the call – we are going to shut them all down in 30 min, in 15 min?

Aaronson: It's not as simple as cutting the power. That's not how this is going to work but there is again, there is this shared responsibility among the sector.

Johnson: Who makes the call?

Aaronson: I do not know the answer to that question [29].

Mr. Aaronson's is Managing Director for Cyber and Infrastructure Security at EEI.

Congressman Trent Franks, R Az introduced HR 2417, the SHEILD Act, on 6/18/2013. The bill would give FERC the authority to require owners and operators of the bulk power system to take measures to protect the grid from GMD or EMP attack. The costs would be recovered by raising regulated rates.

Franks states he had been led to believe that his bill would be brought to the House floor for a vote. But he states House Energy and Commerce Committee Chairman Fred Upton R, Mich., let it die in committee. He has been unable to get an explanation from Upton [30].

Between 2011 and 2016, Mr. Upton has received $1,180,000 in campaign contributions from the electric utility industry [31].

The electric utility industry is heavily involved in campaign donations. During the 2014 federal election cycle, the electric utility industry made $21.6 million in campaign contributions [32]. The electrical utility industry is particularly involved in state politics. For instance, in Florida, between 2004 and 2012 electric utility companies donated $18 million to legislative and state political campaigns. In that state, the electric utilities employ one lobbyist for every two legislators [33].

Electric utility revenue in 2015 was 391 billion dollars [34].

Electromagnetic pulse

Of the scenarios that might lead to electrical network collapse, EMP has received the widest public attention. It has been the subject of television series, films, and novels. HEMP (for high altitude) is the more accurate acronym, but as media and the public use EMP, we will use both interchangeably.

The issue has become highly politicized. The most prominent article in the media against EMP as a threat is by Patrick Disney, "The Campaign to Terrify You about EMP" published in the Atlantic in 2011. "From Newt Gingrich to a Congressional 'EMP Caucus', some conservatives warn the electronic-frying blast could pose gravely underestimated dangers on the U.S.….Ballistic missile defense seems to be the panacea for this groups concern, though a generous dose of preemption and war on terror are often prescribed as well" [35].

As of 2009, Mr. Disney was acting Policy Director for the National Iranian American Council (NIAC). NIAC has been accused of acting as a lobby for the Islamic Republic of Iran [36].

Mr. Disney is quoted as stating his strategy, in advancing an Iranian interest, is to "create a media controversy" [36].

The campaign to discredit EMP has been largely successful. To a very large part of the body politic EMP is identified as a cause limited to the far right.

A high-altitude electromagnetic pulse (EMP) is produced when a nuclear device is detonated above the atmosphere. No radiation, blast, or shock wave is felt on the ground, nor are there any adverse health effects, but electromagnetic fields reach the surface.

An EMP has three components, E1 through E3, defined by speed of the pulse. Each has specific characteristics, and specific potential effects on the grid. E1, the first and fastest component, affects primarily microelectronics. E3, the later and slower component, affects devices attached to long conductive wires and cables, especially high-voltage transformers.

A single nuclear blast will generate an EMP encompassing half the continental USA [37]. Two or three explosions, over different areas, would blanket the entire continental USA.

The potential impact of an EMP is determined by the altitude of the nuclear detonation, the gamma yield of the device, the distance from the detonation point, the strength and direction of the earth's magnetic field at locations within the blast zone and the vulnerability of the infrastructures exposed. The E1 gamma signal is greatest for bursts between 50 and 100 km altitude. E3 signals are optimized at bursts between 130 and 500 km altitude, much greater heights than for E1 [38]. Higher altitude widens the area covered, but at the expense of field levels. The 1963 atmospheric test ban has prevented further testing.

E1 and its effects

The E1 pulse ("fast pulse") is due to gamma radiation (photons), generated by a nuclear detonation at high altitude, colliding with atoms in the upper atmosphere. The collisions cause electrons to be stripped from the atoms, with the resultant flow of electrons traveling downward to earth at near the speed of light. The interaction of the electrons with the earth's magnetic field turns the flow into a transverse current that radiates forward as an intense electromagnetic wave. The field generates extremely high voltages and current in electrical conductors that can exceed the voltage tolerance of many electronic devices. All this occurs within a few tens of nanoseconds.

The Congressional EMP Commission postulated that E1 would have its primary impact on microelectronics, especially SCADAs (Supervisory Control and Data Acquisition), DCSs (digital control systems), and PLCs (programmable logic controllers). These are the small computers, numbering now in the millions, that allow for the unmanned operation of our infrastructure.

To assess the vulnerability of SCADAs to EMP, and therefore the vulnerability of our infrastructure, the EMP Commission funded a series of tests, exposing SCADA components to both radiated electric fields and injected voltages on cables connected to the components. The intent was to observe the response of the equipment, when in an operational mode, to electromagnetic energy simulating an EMP. "The bottom line observation at the end of the testing was that every system tested failed when exposed to the simulated EMP environment" [6].

E1 can generate voltages of 50,000 V. Normal operating voltages of today's miniaturized electronics tend to be only a few (3-4) volts. States the EMP Commission: "The large number and widespread reliance on such systems by all the nation's critical infrastructures represent a systemic threat to their continued operation following an EMP event" [39]. A scenario seen in films is all automobiles and trucks being rendered inoperable. This would not be the case. Modern automobiles have as many as 100 microprocessors that control virtually all functions, but the vulnerability has been reduced by the increased application of electromagnetic compatibility standards. The EMP Commission found that only minor damage occurred at an E1 field level of 50 kV/m, but there were minor disruptions of normal operations at lower peak levels as well [40].

There is a self-published post (J. Steinberger, Nobel laureate physics, 1988) disputing the potential effects of E1 [41]. This is an isolated opinion.

Shielding against E1 could theoretically be accomplished through the construction of a Faraday cage around specific components or an entire facility. The cage is composed of conductive materials and an insulation barrier that absorbs pulse energy and channels it directly into the ground. The cage shields out the EM signals by "shorting out" the electric field and reflecting it.

To be an effective Faraday cage, the conductive case must totally enclose the system. Any aperture, even microscopic seams between metal plates, can compromise the protection. To be useful, however, a device must have some connection with the outside world and not be completely isolated. Surge protective devices can be used on metallic cables to prevent large currents from entering a device, or the metallic cables can be replaced by fiber optic cables without any accompanying metal. The US Military has taken extensive measures to protect ("harden") its equipment against E1. "On the civilian side, the problem has not really been addressed" [42].

E3 and its effects

E3 is caused by the motion of ionized bomb debris and atmosphere relative to the geomagnetic field, resulting in a perturbation of that field. This induces currents of thousands of amperes in long conductors such as transmission lines that are several kilometers or greater in length. Direct currents of hundreds to thousands of amperes will flow into transformers. As the length of the conductor increases, the amperage amplifies.

The physics of E3 are similar to that of a GMD, but not identical. GMD comes from charged particles showering down from space creating current flow in the ionosphere. These currents create magnetic fields on the ground. A nuclear burst on the other hand generates particles which create a magnetic bubble that pushes on the earth's magnetic field producing a changing magnetic field at the Earth's surface. A geomagnetic storm will have substorms that can move over the Earth for more than 1 day, while the E3 HEMP occurs only immediately following a nuclear burst.

There are three studies on the potential effects of a HEMP E3 on the power grid.

The first study, published in 1991, found there would be little damage [43]. Although supporting the utility industry's position, it has not been subsequently cited by either NERC or the industry. The study is criticized for expressing a smaller threat intensity [44]. The second, published in 2010 by Metatech, calculated that a nuclear detonation 170 km over the USA would collapse the entire US power grid [45]. The third study, by EPRI (an organization funded by the electric utility industry) published in February 2017, asserts that a single high-altitude burst over the continental USA would damage only a few, widely scattered transformers [46]. The study is disputed for underestimating threat levels and using erroneous models [44].

These results are incompatible. One's interpretation of the studies on E3 (and GMD) is based largely on the credibility one gives to the underlying Commission or Institute, and not the published calculations.

FERC has decided not to proceed with a GMD standard that includes EMP [47]. It will be recalled the GMD standard is 8 V/km. The EMP Commission, utilizing unclassified measured data from the Soviet era nuclear tests, found an expected peak level for E3 HEMP for a detonation over the continental USA would be 85 V/km [48].

The position of the electric utility industry is that E3 from a nuclear detonation is not a critical threat [49]. Others have come to a different conclusion. Israel has hardened her grid [50]. She perceives herself to face an existential threat, and it is not the Sun.

The electric utility industry states the cost of hardening the grid against EMP is the government's responsibility, not the industry's [51].

Cyberattack

The vulnerability from a cyberattack is exponentially magnified by our dependence on SCADAs.

In 2010, a computer worm attacking SCADA systems was detected. Although widely spread, it was designed to only attack SCADA systems manufactured by Siemens for P-1 centrifuges of the Iranian nuclear enrichment program. The attack destroyed between 10 and 20% of Iranian centrifuges. Iran's program was likely only briefly disrupted [52]. In December 2015, a cyberattack was directed against the Ukrainian power grid. It caused little damage as the grid was not fully automated.

There is an argument that the cyber threat is exaggerated. Thomas Rid states that viruses and malware cannot at present collapse the electric grid. "(The world has) never seen a cyber- attack kill a single human being or destroy a building" [53]. The electric utility industry offers a similar perspective. In testimony on cybersecurity before the Senate Homeland Security and Governmental Affairs Committee, its representative states that "There are a lot of threats to the grid…..from squirrels to nation states, and frankly, there have been more blackouts as a result of squirrels (gnawing wire insulation) then there are from nation states" [54].

Others however express concern [55]. Moreover, in a report by the Department of Defense in 2017, it is noted that "the cyber threat to critical US infrastructure is outpacing efforts to reduce pervasive vulnerabilities." [56] That report notes that "due to our extreme dependence on vulnerable information systems, the United States today lives in a virtual glass house" [57].

On March 15, 2018, the Department of Homeland Security issued an alert that the Russian government had engineered a series of cyberattacks targeting American and European nuclear power plants and water and electric systems [58]. It is reported these attacks could allow Russia to sabotage or shut down power plants at will [59].

The ability to operate a system in the absence of computer-driven actions is fast disappearing. The electric power industry spends over $1.4 billion dollars annually to replace electromechanical systems and devices that involve manual operation with new SCADA equipment [60]. With modest increases in efficiency come exponential increases in vulnerability. The extent to which reduced labor costs (and perhaps reduced energy costs) are passed on to the public is uncertain.

Kinetic attack

An internal FERC memo obtained by the press in March 2012 states that "destroy nine interconnector substations and a transformer manufacturer and the entire United States grid would be down for 18 months, possibly longer" [61]. The mechanism is through the megawatts of voltage that would be dumped onto other transformers, causing them to overheat and in cascading fashion cause the entire system overload and fail.

At Metcalf California (outside of San Jose) on April 16, 2013, a HV Transformer owned by PG&E sustained what NERC and PG&E claimed was merely an act of vandalism [1]. Footprints suggested as many as 6 men executed the attack. They left no fingerprints, not even on the expended shell casings [1]. US FERC Chairman Wellinghoff concluded that the attack was a dry run for future operations [62].

Information on how to sabotage transformers has been available online [63].

There is a disincentive for management to invest in security. As stated in a report by the Electric Research Power Institute: "Security measures, in themselves, are cost items, with no direct monetary return. The benefits are in the avoided costs of potential attacks whose probability is generally not known. This makes cost-justification very difficult" [64].

CEO pay at large American companies is based on the Harvard Business School theory that the best measure of managerial performance is a company's stock price. This does not necessarily align the interests of CEOs with shareholders, let alone the public. It "encourages short-term boosts to profits rather than investing for long term growth" [65].

In 2014, the CEO of PG&E, Anthony Early Jr., had a compensation of $11.6 million dollars. Over 90% was from bonuses based on stock performance. The President of PG&E, Christopher Johns, had a compensation of $6 million dollars [66]. There is no evidence, however, that any of this is in play in the positions of the electric utility industry vis-à-vis securing the grid. States PG&E spokesman Jonathan Marshall, "The majority of compensation for senior executives is shareholder funded and dependent on achieving targets related to safety, reliability and other results" [66].

Consequences of a sustained power outage

The EMP Commission states "Should significant parts of the electrical power infrastructure be lost for any substantial period of time, the Commission believes that the consequences are likely to be catastrophic, and many people will die for the lack of the basic elements necessary to sustain life in dense urban and suburban communities." [67].

Space constraints preclude discussion on how the loss of the grid would render synthesis and distribution of oil and gas inoperative. Telecommunications would collapse, as would finance and banking. Virtually all technology, infrastructure, and services require electricity.

An EMP attack that collapses the electric power grid will collapse the water infrastructure—the delivery and purification of water and the removal and treatment of wastewater and sewage. Outbreaks that would result from the failure of these systems include cholera. It is problematic if fuel will be available to boil water. Lack of water will cause death in 3 to 4 days [68].

Food production would also collapse. Crops and livestock require water delivered by electronically powered pumps. Tractors, harvesters, and other farm equipment run on petroleum products supplied by an infrastructure (pumps, pipelines) that require electricity. The plants that make fertilizer, insecticides, and feed also require electricity. Gas pumps that fuel the trucks that distribute food require electricity. Food processing requires electricity.

In 1900, nearly 40% of the population lived on farms. That percentage is now less than 2% [69]. It is through technology that 2% of the population can feed the other 98% [68]. The acreage under cultivation today is only 6% more than in 1900, yet productivity has increased 50 fold [69].

As stated by Dr. Lowell L Wood in Congressional testimony:

> "If we were no longer able to fuel our agricultural machine in the country, the food production of the country would simply stop, because we do not have the horses and mules that used to tow agricultural gear around in the 1880s and 1890s".
> "So the situation would be exceedingly adverse if both electricity and the fuel that electricity moves around the country……… stayed away for a substantial period of time, we would miss the harvest, and we would starve the following winter" [70].

People can live for 1–2 months without food, but after 5 days, they have difficulty thinking and at 2 weeks they are incapacitated [68]. There is typically a 30-day perishable food supply at regional warehouses but most would be destroyed with the loss of refrigeration [69]. The EMP Commission has suggested food be stockpiled for a possible EMP event.

A prescription for failure

Even if all the recommendations of the Congressional EMP Commission were

Even if all the recommendations of the Congressional EMP Commission were implemented, there is no guarantee that the grid will not sustain a prolonged collapse. There should therefore be contingency plans for such a failure.

There is also another consideration. The foundational pillars of prior American nuclear defense policy, in today's climate, are of uncertain validity. Mutual assured destruction is the Maginot line of the 21st century. Nonproliferation will prove difficult to resurrect.

The consequences of a widespread nuclear attack have been positioned to the public as massive deaths from blast effects, and then further lingering deaths from the effects of radiation. We suspect there will be no electricity, and there will be no electricity for a very long time.

There should be an actionable plan in anticipation of a possible prolonged collapse of the grid—a retro-structure and a skill set to provide a framework for survival. Our sense is there is no plan.

Abbreviations

CEO: Chief executive officer

CME: Coronal mass ejection

DCS: Digital control systems

EEI: Edison Electric Institute

EMP: Electromagnetic pulse

EPRI: Electric Power Research Institute

FERC: Federal Energy Regulatory Commission

GMD: Geomagnetic disturbance

HEMP: High altitude electromagnetic pulse

HV: High voltage

NAS: National Academy of Sciences

NERC: North American Electric Reliability Corporation

NIAC: National Iranian American Council

PG&E: Pacific Gas and Electric

PLS: Programmable logic controllers

SCADA: Supervisory control and data acquisition

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